Pathways to Discovery in Astronomy and Astrophysics for the 2020s: Highlights of a Decadal Survey (2023)

DETAILS

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PATHWAYS TO DISCOVERY

in Astronomy and Astrophysics for the 2020s

Highlights of a Decadal Survey

NATIONAL ACADEMIES *Sciences Engineering Medicine*

About

Decadal surveys of the National Academies of Sciences, Engineering, and Medicine bring together leading experts to identify a field's most compelling science challenges and frontiers for the next decade and beyond. This booklet highlights key themes and recommendations from the most recent decadal survey for astronomy and astrophysics, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*.[1]

This decadal survey represents a monumental undertaking, involving approximately 150 experts who collectively reviewed nearly 900 community white papers during a deliberative process spanning more than 2 years. The resulting report serves as a guide for scientists, policy makers, and federal agencies invested in advancing visionary research in the astronomical sciences. It outlines priority areas for exploring the cosmos, along with the investments needed to cultivate and sustain the people who drive innovation and discovery, the tools to carry out the science, and the research insights that will expand humanity's horizons.

[1] National Academies of Sciences, Engineering, and Medicine, 2023, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, Washington, DC: The National Academies Press, https://doi.org/10.17226/26141.

CONTENTS

OUR SHARED **QUEST**

We live in a time of extraordinary discovery and progress in astronomy and astrophysics.

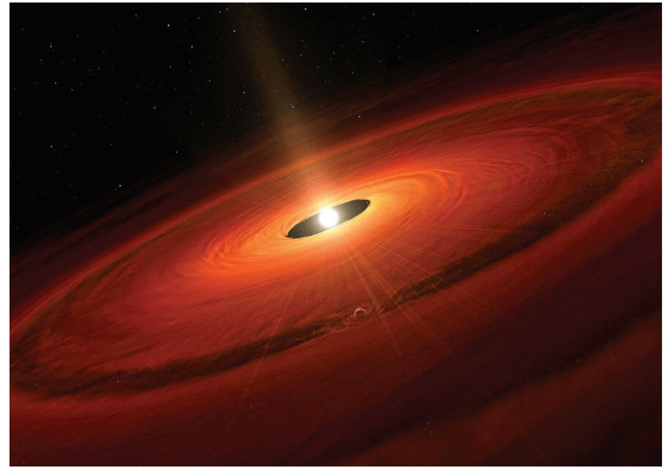
What's out there in the cosmos? Where did we come from? Are we alone?

These questions touch the very heart of human identity and curiosity. For millennia, they have motivated a shared quest to probe our surroundings, map the stars, and imagine what lies beyond the horizon.

The answers are closer than ever.

In the past few years, humanity has celebrated the first definitive detection of gravitational waves and imaged the shadow of a black hole. We have gleaned new insights into the birth of galaxies and discovered planets that may be capable of sustaining life. We have sent the world's largest space telescope a million miles from Earth in a bold endeavor to observe what has previously been hidden and unknowable.

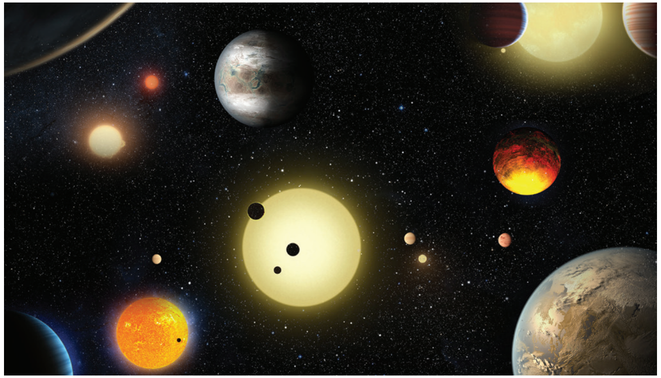
Our ability to grasp the mysteries of the universe has already far exceeded what our predecessors could have imagined. Now, we are poised to do much more. Technological innovations and emerging scientific methods are creating new tools to search for the signatures of life beyond Earth, investigate the origins and nature of our universe, and resolve the inner workings of galaxies.



Artist's rendering of a dust disk and newly formed planet surrounding the star TW Hydrae. Our growing capacity to observe cosmic phenomena enriches our fundamental understanding of the universe.

Worlds and Suns in Context

Exoplanets—planets orbiting stars other than our Sun—have gone from something we could only imagine to something we routinely observe. This transformation has happened in a stunningly short period of time, opening new opportunities to study how planets form, their connections to their parent stars, and what other secrets they may harbor.



Artist's rendering of planets discovered by NASA's Kepler space telescope. To date, more than 4,000 exoplanets have been discovered, about 20 of which are similar to Earth in terms of size, temperature, and the potential for liquid water.

A Universe Teeming with Worlds

Scientists long speculated that planets exist outside of our solar system but did not confirm this until just a few decades ago. When the first exoplanet was documented in 1992, researchers debated how many such planets might be out there. Were they rare, making our solar system unique with its bounty of eight planets? Or did most stars host their own planetary systems, spinning in countless intricate dances across the universe?

Recent decades have answered that question with an explosion of exoplanet observations. To date, scientists have documented more than 5,000 planets, with new ones now being discovered every few days. These discoveries suggest that there are likely many more planets than stars in the universe.

Searching for Signs of Life

What wonders might each world hold? Perhaps the most intriguing possibility is life. Scientists have already found about 20 Earth-sized planets that are in the "habitable zone"—at a distance from their parent star that makes them neither too hot nor too cold to allow for liquid water. Measurements suggest that around 30 percent of stars host at least one habitable-zone planet.

While much about these planets remains mysterious, new tools are allowing us to learn more about their makeup, origins, orbits, and atmospheres. Spectroscopic measurements, for example, are particularly useful because they offer information about the chemical composition of a planet's atmosphere—data that can help us find habitable planets and even provide evidence of active life.

The coming decades will set humanity down a path to determine if we are alone.

PRIORITY AREA:

Pathways to Habitable Worlds

Identifying habitable worlds is a key priority for the coming decade. This effort includes characterizing which exoplanets are most Earth-like, determining which ones are most feasible to study, and employing a variety of techniques to search for signatures of life.

Unraveling the many cosmological mysteries will require a particularly close interplay among theory, simulation, observations, and laboratory experiments.

New Messengers and New Physics

Astrophysics teaches us to expect the unexpected—to embrace surprises as a way to refine or fundamentally reconsider how we view the universe. As we expand our capacity to observe, simulate, and experiment with fundamental physical processes, we unlock new opportunities to test and reshape our theories about how the universe works.

Going the Distance

Emerging observational capabilities allow us to tap signals from the extreme reaches of space and time. Many of these signals or "messengers" have traveled billions of years before encountering our instruments, carrying with them the traces of ancient events.

For example, observations using the full electromagnetic spectrum allow us to detect ever fainter sources of light, effectively peering into the distant past for a view of the young universe. At the same time, innovative methods to overcome distortion offer views of distant phenomena with unprecedented clarity. Observing the sky repeatedly over time, over multiple wavelengths and messengers, provides a powerful window into cosmic dynamics.

New Ways of Seeing

To augment and amplify the wide range of light-based observations, researchers can now tap into entirely new types of messengers such as particles, gravitational waves, and neutrinos. For example, in the mid-2010s,

The shadow of the black hole at the center of the Messier 87 galaxy. This image, generated with data from eight telescopes worldwide, is the first to visually capture a black hole and represents the culmination of decades of theoretical, modeling, and observational work.

complementary observations of gravitational waves and light revealed a new picture of a pair of merging neutron stars. Just as we combine sight, sound, taste, smell, and touch to sense our everyday surroundings, combining multiple types of observations provides a deeper understanding of our universe.

These developments have greatly enriched the intellectual feedbacks between astronomy and physics. They also bring us closer to thrilling new insights into many long-standing mysteries, including the nature of dark matter and dark energy, the origins of the elements that comprise our bodies and our planet, the makeup of the gas between galaxies, and the processes that formed the universe.

Cosmic Ecosystems

Galaxies enchant us with their explosive abundance of cosmic bodies, often standing out as swirling hives of activity against the dark emptiness of space. While it is tempting to view galaxies as independent and self-contained, in truth they are intricately connected with each other and the broader space environment in ways that we are only beginning to grasp.

Finding Feedbacks

On Earth, feedbacks are integral to ecosystems—from forests to coral reefs. Similarly, scientists are learning that feedbacks are an essential part of the workings of the cosmos, with different components moving, using, and recycling matter and energy in a complex interconnected web.

This means that even small-scale processes can have surprising impacts on large-scale systems. For example, it is thought that ionizing radiation produced by some of the first stars and black holes—relatively small bodies in the scheme of things—propagated across the cosmos and contributed to the conversion of most of the hydrogen in the universe from a neutral to an ionized state, a phase transition with massive implications for the evolution of the young universe.

Synthesizing Across Scales

The flow of matter and energy throughout the cosmic ecosystem—combined with the effects of gravity and feedbacks—likely explains many of the similarities and differences between galaxies, as well as the internal

PRIORITY AREA:

New Windows on the Dynamic Universe

Over the next decade, emerging techniques will expand our ability to study the most energetic processes in the universe. Combining complementary observations will provide a potent new lens on what happens when stars collapse, including the formation of neutron stars and white dwarfs; stellar explosions and black hole collisions; and the birth of the universe itself.

We stand on the threshold of new endeavors that will transform not only our understanding of the universe and the processes and physical paradigms that govern it but also humanity's place in it.

PRIORITY AREA:

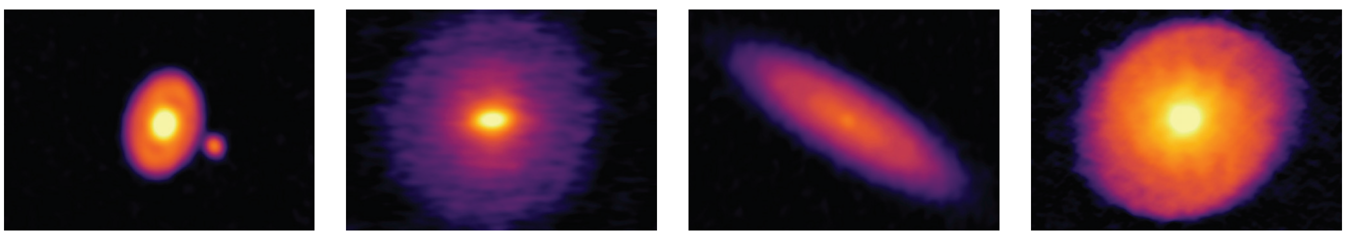
Unveiling the Drivers of Galaxy Growth

Research to resolve the origins and workings of galaxies is a key priority. New observational capabilities, combined with computational techniques and theoretical developments, are poised to revolutionize our understanding of galaxies on all scales.

dynamics that produce the stars and planets within galaxies. But the details of this process have been elusive. How do these flows disburse heavy elements, from the carbon in our bones to the rare-Earth metals in our phones? How do they determine the distribution of gas between stars and between galaxies? How do some galaxies get fuel to keep forming stars, and what causes others to become quiescent?

Answering these questions requires studies at an enormous range of length and time scales. Knitting together observations of processes often spanning 10 or more orders of magnitude pushes the limits of our scientific capabilities. A confluence of advances in theory, computational modeling, and new observational capabilities is opening new opportunities to investigate stars, black holes, supernovae, and other structures within galaxies; the interactions between galaxies and the broader cosmic ecosystem; and what these relationships may reveal about how galaxies form.

30 Doradus, an extremely active star-forming region of the Large Magellanic Cloud galaxy. Observing such stellar nurseries using multiple wavelengths can provide clues about how galaxies form and evolve and how newly formed massive stars provide energy feedback in the form of stellar winds and supernovae.



Images of the dust disks surrounding young stars. Comparing these structures offers insights on planet formation and gas flows within galaxies.

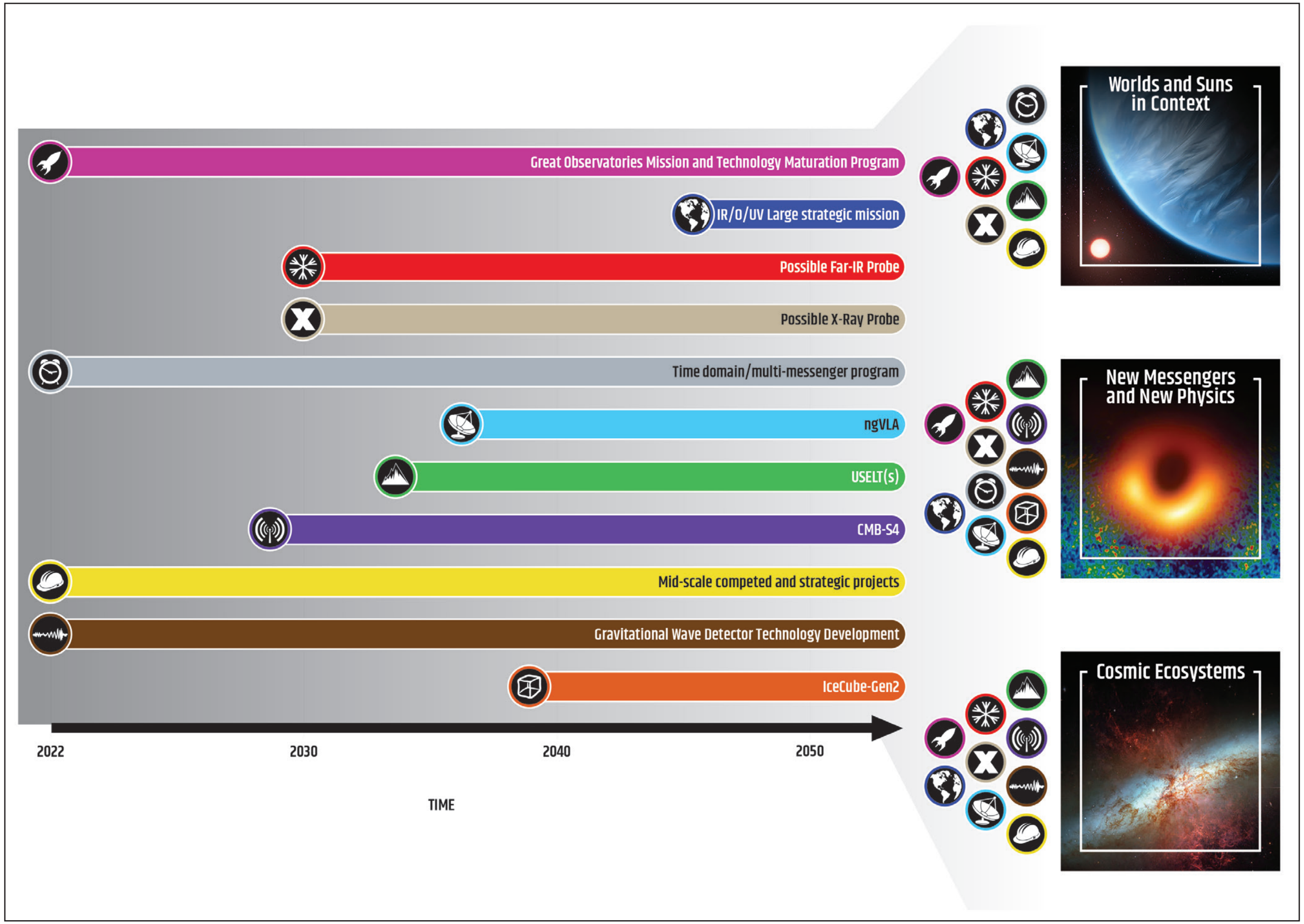
PATHWAYS TO **DISCOVERY**

The program laid out in this report represents a collective vision for the future and will require the engagement of a broad community to advance.

A decadal survey not only captures a vision of what we may achieve but also charts a clear path to achieving it. What investments are needed today to lay the groundwork for ambitious future missions? How can we reap the greatest benefit from past investments and current endeavors? How can we craft programs that are responsive to evolving scientific knowledge and poised to take advantage of future technological advancements?

Enabling breakthroughs in priority scientific areas requires a range of strategic investments at multiple scales. It requires space-based missions that will venture far from Earth to bring a profoundly new perspective on our place in the universe. It requires ground-based initiatives that will probe new facets of physics and observe the universe with unprecedented sensitivity. And it requires comprehensive strategies to support the field's foundations by investing in the people who drive innovation and the facilities and technologies that enable the science.

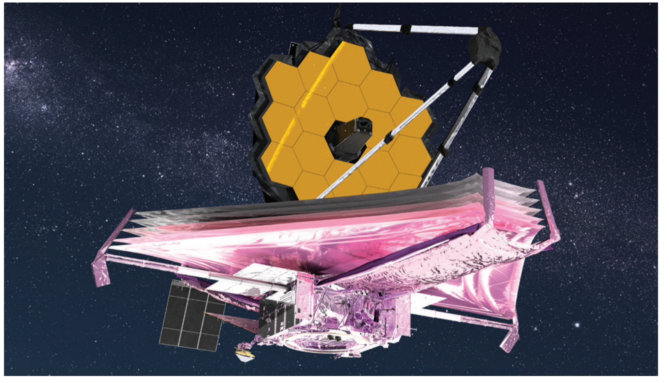
We are poised to tackle some questions that are so grand that the facilities and instruments needed to address them require vision and commitments that span generations and borders. To realize the bold vision outlined in this decadal survey requires a re-imagining of the ways in which large missions are developed and implemented. While the substantial cost of envisioned missions likely limits the ability to pursue all of the worthy ideas simultaneously, setting priorities among those ideas, based on the scientific opportunities they present, can help us to maximize the return on investment. With more early investments in co-maturing mission concepts and technologies, with room for checks and course corrections along the way, and with a workforce that utilizes the broadest range of human talent, we can achieve incredible scientific gains.



Programs and projects recommended in the decadal survey. Icons on the timelines indicate the projected start date (for programs) or the year in which scientific operations would begin (for missions and observatories). Icons next to the boxes at the right indicate which of the three priority scientific areas each program or project would advance.

Space-Based Initiatives

Since its founding, the National Aeronautics and Space Administration (NASA) has pioneered audacious, far-reaching missions to explore the cosmos from space. Taking advantage of the extreme conditions of space and unique vantage points not attainable anywhere on Earth, these programs have dramatically expanded scientific knowledge and positioned the United States as a global leader in astronomy and astrophysics.



The next decade and beyond presents opportunities to build on these successes and extend our knowledge into the next frontiers. A suite of overlapping missions to observe the universe using multiple wavelengths will provide the different and complementary views of the cosmos required to address the full set of Astro2020 scientific objectives.

A New Approach for a New Generation of Space Telescopes

To enable the strategic missions envisioned for the

The James Webb Space Telescope (top), launched in 2021. At bottom, a comparison of images of the Carina Nebula obtained from the Hubble (left) and Webb (right) space telescopes illustrates the increased clarity and detail achieved with Webb, a mission reaffirmed as a top priority in the National Academies' last decadal survey (Astro2010) that is now bringing groundbreaking insights. Astro2020 recommends launching a new space telescope in the 2040s designed specifically to search for signatures of life.

coming decades, the decadal survey recommends a new approach to co-developing the science, mission architectures, and technologies for space telescopes. A Great Observatories Mission and Technology Maturation Program would guide the maturation and provide checks to adjust the course along the way in order to ensure consistency with the recommended cost and schedule targets.

Top Priorities for Large Space-Based Initiatives

Key priorities recommended for a Great Observatories Mission and Technology Maturation Program include an infrared/optical/ultraviolet (IR/O/UV) space observatory, a far-infrared spectroscopy and imaging mission, and a high spatial resolution X-ray strategic mission.

A large IR/O/UV space telescope designed to search for life on other planets is the priority to enter the maturation program first. This flagship mission would combine high-contrast imaging (capable of observing planets 10 billion times fainter than their star) with spectroscopic capabilities covering near-infrared, visible, and ultraviolet wavelengths to study the atmospheres of Earth-like, habitable-zone planets, and it would be transformative for general astrophysics.

Other high priorities include

- An astrophysics probe-class mission program, with recommended initial projects including a far-infrared spectroscopy or imaging mission to provide broad wavelength coverage and scientific balance and an X-ray probe to investigate highly energetic phenomena
- A time-domain and multi-messenger program of small- and medium-scale missions to sustain space-based, electromagnetic capabilities for studying transient phenomena, such as those discovered via gravitational waves and neutrinos

TOP-PRIORITY RECOMMENDATION:

Large IR/O/UV Space Telescope

Scientific Goals

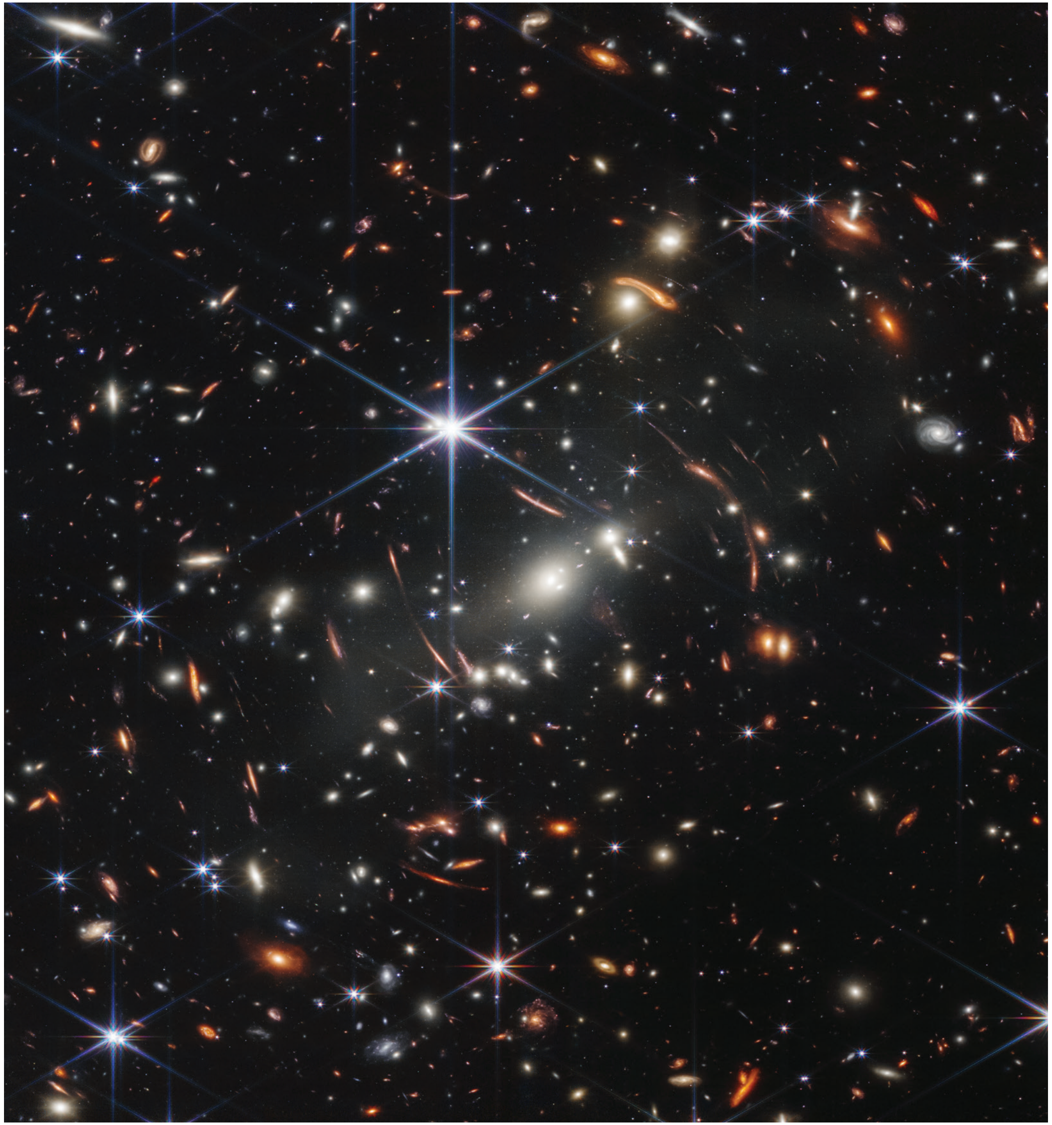
- Search for signatures of life on around 25 habitable-zone planets
- Transform astrophysics more broadly

Specifications

- Around 6-meter aperture
- High-contrast imaging
- IR/O/UV spectroscopic capabilities

Timeline

- 2020s: planning and maturation
- 2030s: implementation
- 2040s: launch



Key Recommendations[2] for Space-Based Initiatives

IMPLEMENTING THE NEXT GREAT OBSERVATORIES

Great Observatories Mission and Technology Maturation Program

Given the large costs and development time scales for the next generation of space telescopes, the decadal survey recommends that NASA create the Great Observatories Mission and Technology Maturation Program as a new approach for planning and implementing large missions. The program would co-mature science, mission architecture, and technology to refine cost and scope, ensuring consistency with decadal recommendations. The first entrant for the maturation program should be a large IR/O/UV space telescope. The second entrants should be strategic far-infrared and X-ray missions.

Large IR/O/UV Space Telescope

The decadal survey recommends a large (around 6-meter diameter) IR/O/UV space telescope with high-contrast imaging and spectroscopy as the first mission to enter the Great Observatories Mission and Technology Maturation Program. This is an ambitious mission with the goal of searching for biosignatures from habitable-zone exoplanets and providing a powerful new facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade with a target launch in the first half of the 2040s.

[2] This booklet highlights a selected subset of recommendations that have been condensed and paraphrased. For a full list of the recommendations in context, as well as approximate financial estimates for the recommended programs, access the full report at https://doi.org/10.17226/26141.

SMALL- AND MEDIUM-SCALE INITIATIVES FOR SUSTAINING AND BALANCING THE SCIENCE

Time Domain and Multi-Messenger Follow-Up Program

Many of the most exciting opportunities in multi-messenger astrophysics rely on observations of transient astrophysical phenomena discovered via gravitational waves and neutrinos. However, these events also require electromagnetic observations across the spectrum for identification and further study. NASA should establish a time-domain program of small- to medium-scale missions to sustain the necessary suite of space-based electromagnetic capabilities required to study transient and time-variable phenomena, and to follow-up multi-messenger events.

Astrophysics Probe Mission Program

The large gap in cost and capability between medium-class Explorer missions and large strategic missions is a significant impediment to achieving the broad set of decadal science priorities. Therefore, NASA should institute a new Probe-class line of missions, with mission proposals competed based on priority areas identified by decadal surveys. The first two priorities for probe-class missions should be a far-infrared probe and an X-ray probe. The first Probe-class mission should commence within this decade.

Maintain Explorer Program Launch Rates

NASA's augmentation of the Explorer program in response to a recommendation from the National Academies' last decadal survey (Astro2010) has resulted in an increased rate of proposal opportunities and launches, yielding a tremendous science output. NASA should maintain Explorer launch rates at the level specified in *New Worlds, New Horizons in Astronomy and Astrophysics.*[3]

[3] National Research Council, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, Washington, DC: The National Academies Press, https://doi.org/10.17226/12951.

Ground-Based Initiatives

Recent years have seen exceptional innovation and global collaboration in ground-based infrastructure for astronomy and astrophysics research, pushing the boundaries of our observational capabilities to elucidate the fundamental physical processes of our universe.

Ground-based instruments offer numerous benefits—avoiding the operational constraints of space, they can be constructed and maintained in place, often allowing them to be used by a broader community of scientists and for a broader array of purposes. With their support for a wide range of ground-based initiatives, the National Science Foundation (NSF) and the U.S. Department of Energy (DOE) put U.S. scientists at the forefront of discovery and uphold our nation's tradition as a key partner in global-scale scientific initiatives.

Top Priorities for Large Ground-Based Initiatives

Advancing a coordinated U.S. Extremely Large Telescope (ELT) program is the top priority for ground-based initiatives in the coming decade. Two ELTs, the Giant Magellan Telescope and the Thirty Meter Telescope—already well into development and expected to commence operations in the mid-2030s, contingent on a U.S. funding commitment—will offer a powerful combination of capabilities that can be brought to bear on nearly all of the high-priority scientific questions envisioned for the coming decade. The decadal survey recommends investing in at least one of the two ELTs, but a two-telescope program is strongly preferred because it offers the advantage of full-sky coverage and maximizes the amount of observing time accessible to U.S. researchers.

Other high priorities include

- Cosmic Microwave Background Stage 4 (CMB-S4) observatory to trace feedbacks within cosmic ecosystems and search for signals from the Big Bang

- Next Generation Very Large Array (ngVLA) to replace the two existing large radio telescope arrays while improving sensitivity by roughly an order of magnitude

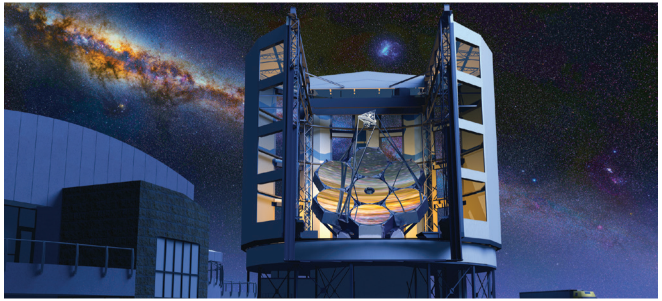
The Vera C. Rubin Observatory, identified as a top priority for ground-based astronomy in the Astro2010 decadal survey. Now nearing the start of operations, the telescope is designed to map the entire Southern sky.

TOP-PRIORITY RECOMMENDATION:
U.S. ELT Program

Scientific Goals
- Capabilities to advance all three high-priority areas of focus (habitable worlds, dynamic universe, cosmic ecosystems)

Components
- Giant Magellan Telescope (GMT)
  - Size: 24.5 m primary mirror
  - Location: Chile
  - Partners: Australia, Brazil, South Korea, United States (most partners are U.S. institutions)
- Thirty Meter Telescope (TMT)
  - Size: 30 m primary mirror
  - Location: Hawai'i or the Canary Islands, Spain
  - Partners: Canada, China, India, Japan, United States (most partners are international)
- NSF National Optical-Infrared Astronomy Research Laboratory (NOIRLab)
  - Engage and represent the United States in ELT program governance and planning
  - Coordinate U.S. access to facilities and data, ensuring that resources are shared by the broadest possible community of U.S. scientists and students

Timeline
- 2020s: funding and implementation
- 2030s: begin operations




Artist's rendering of the mirrors of the Giant Magellan Telescope (left) and the Thirty Meter Telescope (right). The two telescopes, recommended as a top priority for the coming decade, are well into development and expected to commence operations in the mid-2030s, contingent on a U.S. funding commitment.

Key Recommendations for Ground-Based Initiatives

NEW LARGE FACILITIES

U.S. ELT Program

Participation in the U.S. ELT Program is the highest priority recommendation for ground-based astronomy. The ELTs would provide observational capabilities unmatched in space or on the ground and would enable a huge range of new discoveries. NSF should invest in at least one, and ideally both, ELTs—the Giant Magellan Telescope (sited in Chile) and the Thirty Meter Telescope (sited in either Hawai'i or the Canary Islands). NSF should undertake an external review to evaluate the financial and programmatic viability of both proposed U.S. ELT projects.

CMB-S4

Observations of the CMB have been central to establishing the standard model of cosmology, and these measurements are increasingly important for science ranging from the study of galactic ecosystems to the formation of cosmic structure. NSF and DOE should jointly pursue the design and implementation of the next-generation ground-based cosmic microwave background experiment (CMB-S4).

ngVLA

It is of essential importance to astronomy that the Karl Jansky Very Large Array (JVLA) and the Very Long Baseline Array (VLBA) be replaced by an observatory that is roughly an order of magnitude more sensitive. NSF should proceed with a program to support science design, development, cost studies, and antenna prototyping for the ngVLA. After completion of the studies, NSF should convene a review to assess the project's readiness and available budget and proceed with construction if possible.

BALANCING OPERATIONS AND SCIENCE

Balancing Operations Costs and Research Funding for New MREFC Facilities

NSF's Major Research Equipment and Facilities Construction (MREFC) program funds the construction of large facilities, but it leaves the sponsoring divisions responsible for lifetime operations and maintenance costs. These operations costs grow with each new facility added and will significantly restrict NSF's ability to fund research grants and other science programs by mid-decade unless changes are made. NSF should develop a sustainable plan for supporting the operations costs of its astronomical facilities, balanced with funding for scientific research. The addition of new MREFC facilities should be contingent on the implementation of this plan.

Regular Portfolio Reviews for Operating Facilities

NSF's Division of Astronomical Sciences should establish a regular cadence of reviews of its operational portfolio, at a frequency that is sufficient to respond to changes in scientific and strategic priorities in the field. An appropriate target is at least two reviews per decade.

Augmentation of NSF Mid-Scale Program

Mid-scale programs (around $4 million to $100 million) are vital to astronomy research. NSF should create three new tracks within its Mid-Scale Innovations Program. The first track should be for regularly competed, open calls. The second track should solicit proposals in strategically identified priority areas, with time domain astrophysics as the highest priority. The third track should invite ideas for upgrading and developing new instrumentation on existing facilities.

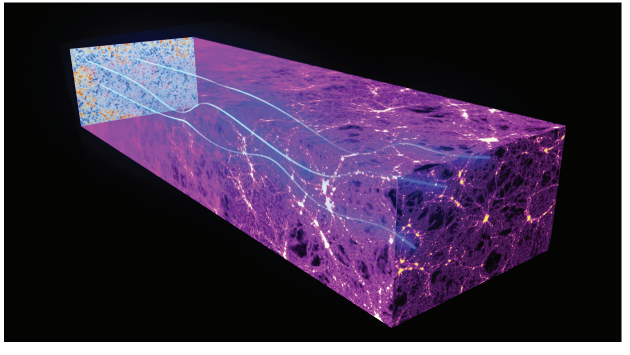
KEY ACTIVITIES IN RELATED FIELDS

Technology Development for Future Gravitational Wave Observatories

Gravitational wave astrophysics is one of the most exciting frontiers in science. The phased upgrades of current generation facilities such as LIGO and technology development for next-generation observatories promise to answer fundamental questions in physics and astronomy. While this project falls under the purview of NSF's Division of Physics, the decadal survey endorses this project as important for meeting its scientific objectives.

IceCube-Generation 2 Neutrino Observatory

The IceCube-Generation 2 Neutrino Observatory would provide significantly enhanced capabilities for detecting high-energy neutrinos, enabling the study of some of the most energetic phenomena in the universe. While this project falls under the purview of NSF's Division of Physics, the decadal survey endorses this project as important for meeting its scientific objectives.



The cosmic microwave background, depicted here as light from the edge of the observable universe moving from left to right, is deflected by mass on its way to Earth.

Supporting the Foundations of Astronomy and Astrophysics

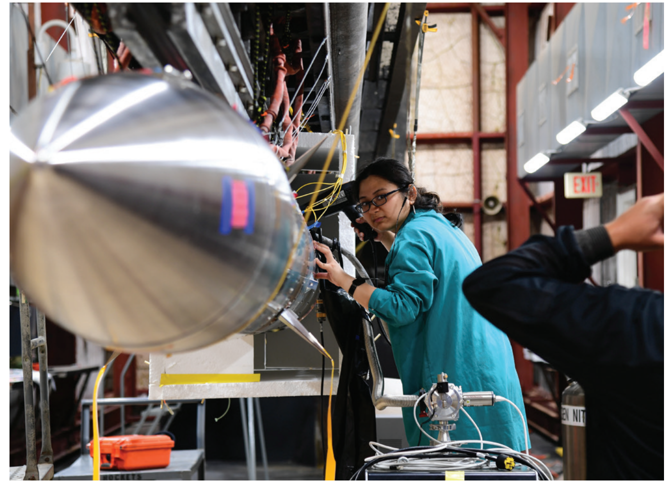
Realizing the full potential of a new generation of space- and ground-based initiatives requires a robust foundation of expertise, technology, and research infrastructure. The decadal survey outlines key actions needed to address gaps, ensure accountability, speed scientific advances, and strengthen the overall U.S. astronomy and astrophysics pipeline in accordance with our nation's values and aspirations.

Driving Innovation

People are the most fundamental component of the research enterprise; human creativity and innovative capacity are vital to transforming data into understanding and discovery. Science is at its most innovative only when it maximizes and fully utilizes the diversity of human talent. In addition, equity demands that scientific endeavors pursued with the nation's resources are done in a manner consistent with the principles of fairness and equal opportunity that are core to society's ideals.

Anyone with the ability and the drive to contribute to scientific discovery should have a fair chance to do so, and be free of fear, harassment, or discrimination. The decadal survey recommends programs to support the scientific workforce, in particular early-career researchers, with a strong emphasis on broadening access, removing barriers to participation, and fostering a safe and inclusive professional environment.

The pursuit of science and scientific excellence is inseparable from the humans who animate it.



(Left) Researchers prepare to test components of the Atacama Large Millimeter/submillimeter Array. (Right) A doctoral student adjusts the rocket payload for the Cosmic Infrared Background Experiment-2.

Sustaining the Engines of Discovery

Tools, technologies, and research coordination are essential to scientific progress. To maximize the utility of scientific resources, it is critical to adequately support the costs of developing, operating, and maintaining state-of-the-art instruments and facilities. To get the greatest possible value out of the data generated, it is vital to adequately support archives, data pipelines, laboratory work, and theoretical tools that provide the cross-cutting foundations for discovery.

Recommendations for Supporting the Foundations for the Profession

DIVERSITY, EQUITY, AND INCLUSION

Demographic Data for Evaluating Equitable Outcomes
NASA, NSF, and DOE should implement a cross-agency working group to establish a consistent format and policy for regularly collecting, evaluating, and publicly reporting demographic data and indicators.

Consideration of Diversity in the Evaluation for Funding Awards
NASA, NSF, and DOE should consider including diversity—of project teams and participants—in the evaluation of funding awards to individual investigators, project and mission teams, and third-party organizations that manage facilities.

Establish Community Astronomy Model
The astronomy community should, through the American Astronomical Society and in partnership with other major professional societies, work with experts from other experienced disciplines (such as archaeology and social sciences) and representatives from local communities to define a Community Astronomy model of engagement that advances scientific research while respecting, empowering, and benefiting local communities.

Treat Discrimination and Harassment as Professional Misconduct
NASA, NSF, DOE, and professional societies should ensure that their scientific integrity policies address harassment and discrimination by individuals as forms of scientific misconduct.

Faculty Diversity and Early-Career Faculty Awards
Racial/ethnic diversity among astronomy faculty remains abysmal. Funding agencies should increase incentives for improving diversity among astronomy and astrophysics faculty, such as increasing the number of awards that invest in the development and retention of early-career faculty and other activities for members of underrepresented groups.

WORKFORCE AND TRAINING

Workforce Development and Bridge Programs
NASA, NSF, and DOE should reinvest in professional workforce diversity programs at the division and directorate levels. "Bridge"-type programs to provide support across academic transitions in the higher-education pipeline and into the professional ranks are especially promising.

Undergraduate and Graduate "Traineeship" Funding
NASA, NSF, and DOE should implement undergraduate and graduate "traineeship" funding to incentivize department- and institution-level commitment to professional workforce development and prioritize interdisciplinary training, diversity, and preparation for a variety of career outcomes.

Independent Postdoctoral Fellowships
NASA and NSF should continue and increase support for postdoctoral fellowships that provide independence while encouraging the development of scientific leaders who advance diversity and inclusive excellence.

DARK SKY AND ENVIRONMENTAL PROTECTION

Moderate Optical Interference from Satellite Constellations

Mega satellite constellations will more significantly affect work in astronomy and astrophysics in the future. NSF should work with the appropriate federal regulatory agencies to develop and implement a regulatory framework to control the impacts of satellite constellations on astronomy.

Reduce Radio-Frequency Interference

To ensure that the skies remain open to radio astronomy, NSF, in partnership with other agencies as appropriate, should support and fund a multi-faceted approach to the avoidance and mitigation of radio-frequency interference.

Climate Change Mitigation Actions

Human-induced climate change will be one of the greatest challenges of this century. The astronomy community can minimize its impact on climate by reducing travel-related carbon emissions. Examples include remote observing, hybrid conferences, and virtual conferences.

Recommendations for Supporting the Foundations for Research

INVESTIGATOR GRANTS AND PROGRAMMATIC BALANCE

Augmentation to NSF Astronomy and Astrophysics Research Grants Program

Over the past decade, there has been a growing imbalance between funding for facility operations and maintenance and for supporting the work of scientists. To support science performed by individual investigators, NSF should increase funding for its Astronomy and Astrophysics Research Grants program by 30 percent over 5 years. This will have the effect of restoring proposal success rates to a healthy competitive level.

Augmentation and Restoration of Annual Proposal Calls for NASA Astrophysics Theory Program

Low funding rates at both NASA and NSF have affected the ability to carry out theoretical investigations, which are crucial for interpreting essentially all signals received from space. NASA's Astrophysics Theory Program should resume an annual cadence and receive a 30 percent funding augmentation over 5 years.

Augmentation and Improved Coordination of Laboratory Astrophysics Funding

Laboratory experiments are crucial for measuring the parameters needed to interpret data from distant astrophysical objects, such as characterizing exoplanet atmospheres. NASA and NSF should convene a panel of experts to identify what laboratory data are needed to support next-generation observatories; identify the resources that can be brought to bear to satisfy those needs; and consider new approaches for building the requisite databases.

Compile and Regularly Report Data on Proposal Submissions and Success Rates

Proposal success rates are an important indicator of program balance, particularly when aiming to give first-time, early-career proposers a realistic chance of success. NASA, NSF, and DOE should release data on proposal success rates on an annual basis, and they should track metrics that allow them to statistically analyze what is being supported.

DATA ANALYSIS AND DATA ARCHIVING

Support for Large Key Projects on MREFC Facilities

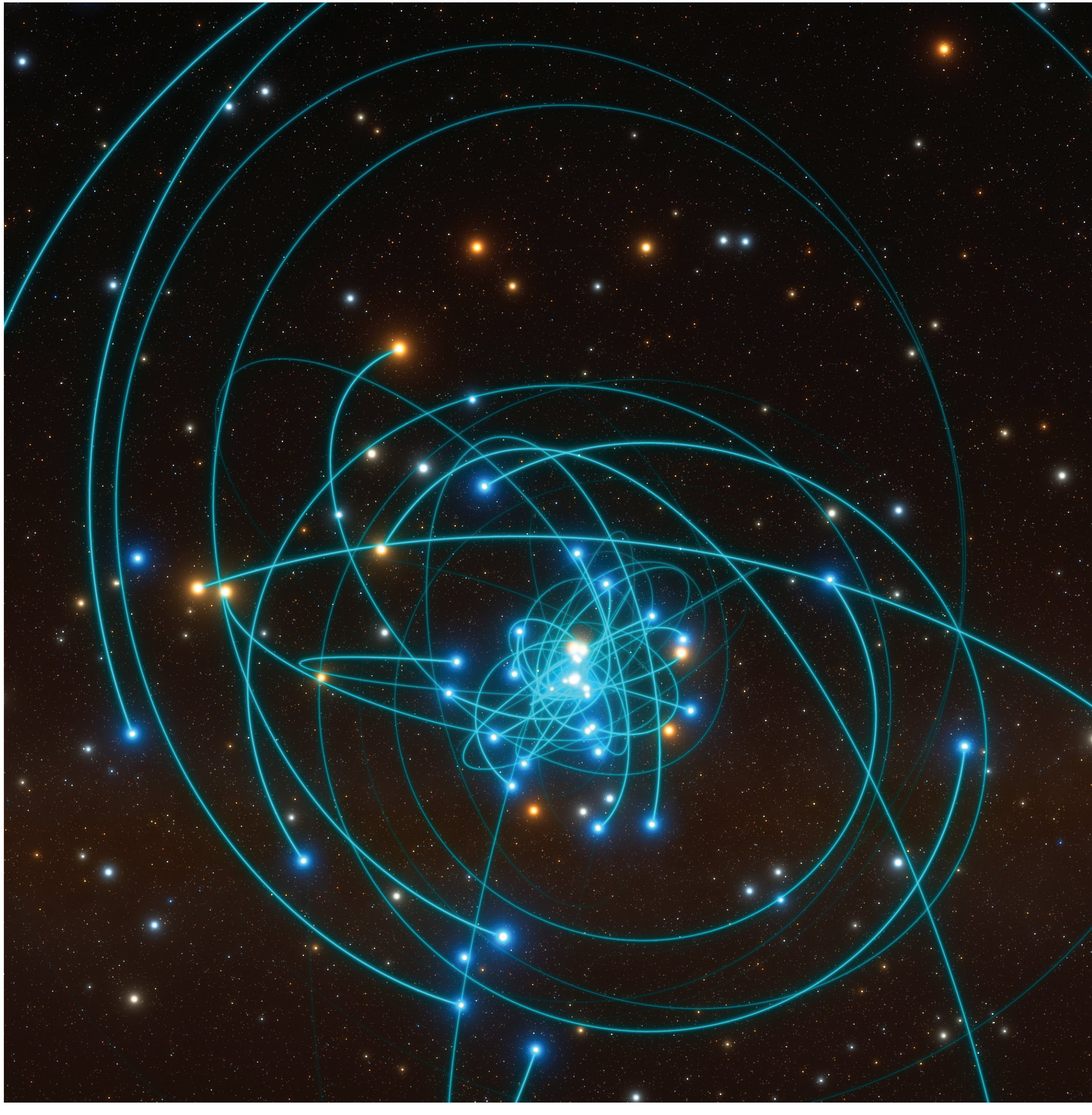
Researchers observing through NSF ground-based facilities must apply for separate funding to support data analysis. This is inefficient and causes delays, hampering the scientific output of the most powerful facilities. NSF should establish a mechanism for funding data analysis and the production of high-level data products for large principal investigator (PI)-led programs on MREFC-scale astronomical facilities.

Improve Coordination Among U.S. Data Centers Supported by NASA and NSF

Astrophysical questions increasingly transcend traditional wavelength, division, and agency boundaries, and there is a growing need for data use across multiple archives. NASA and NSF should explore mechanisms to improve coordination among U.S. archive centers and to create a centralized nexus for interacting with the international archive communities.

Data Pipeline Development, Archiving for Ground-Based Telescopes

Although community-based projects have done much to fill the needs for up-to-date data pipelines and software for ground-based telescopes, NSF could help to provide foundational support for these efforts. NSF and stakeholders should develop a plan to address how to design, build, deploy, and sustain pipelines for producing science-ready data across all general-purpose, ground-based observatories.



Recommendations for Supporting the Foundations for Technology

TECHNOLOGY AND INSTRUMENTATION DEVELOPMENT

Augmentation to NASA Astrophysics Research and Analysis Program

NASA should increase funding levels for the Detector Development and Supporting Technology components of the Astrophysics Research and Analysis Program. Current funding levels are too small to advance technologies to acceptable levels for incorporation in future Explorer, suborbital, and SmallSat missions.

Continue NASA Strategic Astrophysics Technology Program and Expand Eligibility

NASA should continue funding for the Strategic Astrophysics Technology Program and should expand proposal calls to include intermediate-level technology maturation targeted in strategic areas identified for the competed Probe class missions.

Augmentation to NSF Advanced Technologies and Instrumentation Program

Looking to the coming decade, the need to support advanced technologies is even greater than it was a decade ago. NSF should restore the Advanced Technologies and Instrumentation Program to $14 million per year (FY2020)—the same level of support it had in 2010—and further increase it to a target level of $20 million per year (FY2020) by 2028.

Review NASA's Balloon Program for Optimal Balance

Pathways to improving the balloon program include increasing the number of flights, achieving higher float altitudes, making the program accessible to more PIs, and exploring methods for supporting new PIs. NASA should undertake an external review of the balloon program to establish a framework for accomplishing these goals.

CONCLUSION

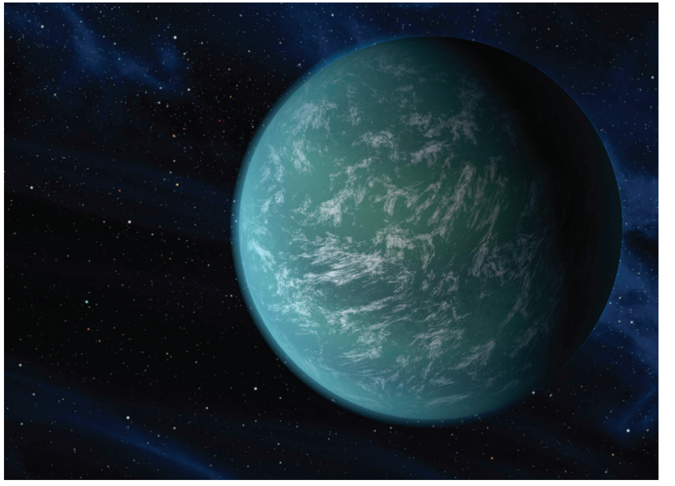
To peer into space is to look back in time. Yet, in our quest to piece together the ancient history of the universe, we are also looking toward the future—a future in which our combined efforts uncover new insights and new possibilities for humanity as a whole. Venturing into the vast expanse of space, searching for signs of life elsewhere in the cosmos, and gazing into the hearts of galaxies offers new perspective on where we came from—and where we might be heading.

The work outlined in this decadal survey spans generations: We are fulfilling the dreams of our parents and laying the groundwork for what our children can achieve.

This work also spans borders: The ambitious endeavors to understand our universe reflect the collective effort of individuals and nations around the world and should encompass all of humanity's diversity.

The societal benefits of investment in astronomy extend far beyond astronomy itself. Discoveries in astronomy and astrophysics inspire people to pursue STEM careers, engage in lifelong learning, and unite around a common purpose.

The achievements of the past several decades have demonstrated the astonishing potential of emerging technologies to reveal what was previously hidden, to answer long-standing questions about our universe, and to capture our collective imagination. With strategic investments to cultivate an innovative workforce, advance tools and technologies, sustain current activities, and construct new frontier facilities, we can achieve much more. We may indeed be on the verge of breakthroughs that will change our understanding of the cosmos. The United States can lead the way.



Artist's rendering of Kepler-22b, the first planet confirmed to orbit in the habitable zone of a Sun-like star. The discovery captured public imagination and kicked off a new wave of inspiring breakthroughs in astronomy and astrophysics.

Realizing the opportunities presented in these pages will only be possible with the continued dedication and energy of the community, the agencies, and the excitement of the nation to explore the cosmos and answer some of humanity's most profound questions.

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